

# NDE of Friction Stir Welds in Aerospace Applications

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## Abstract

Friction Stir Welding (FSW) is a solid state joining process, which utilizes a cylindrical, shouldered pin tool with a radiused tip that is rotated and plunged into the weld joint. Frictional heating beneath the shoulder, and surrounding the pin tip causes the material to plasticize, intermix and consolidate into a weldment without melting the parent material. FSW in aluminum alloys has many advantages such as low distortion and shrinkage, excellent mechanical properties, and no porosity.

However, the propensity of the FSW process to create detrimental defects does exist, and is dependent on FSW parameter limits and controls. Inspection processes for FSW must also be selected and implemented concurrent with the new weld process. This paper describes the efforts by Lockheed Martin and NASA to find proper NDE techniques for detecting and characterizing the anomalies that may be caused by operating outside the envelope of optimized FSW parameters. Potential defects are identified and the results of the exploration of numerous NDE techniques including visual, liquid penetrant, multiple ultrasonic methods, eddy current and conductivity are discussed.

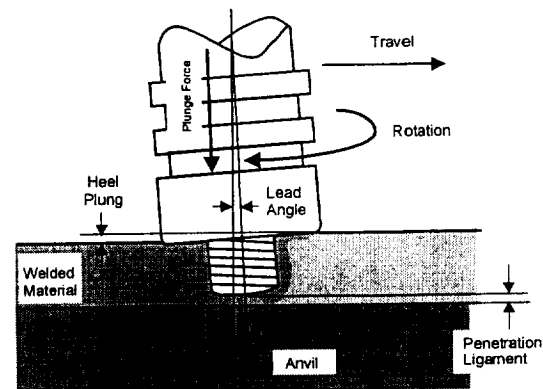
## Friction Stir Welding

Developing and implementing new processes to enhance the performance, reliability and safety of aerospace hardware is a primary ongoing objective for both government and industry programs. TWI in Cambridge, UK, invented friction Stir Welding [1] in the early 90's and Lockheed Martin began its development activities in 1995. FSW development continued at Marshall Space Flight Center (MSFC) through 2001 for various NASA applications including man-rated flight hardware.

Friction Stir Welding is accomplished with both monolithic and multiple piece pin tools rotating at several hundred RPM and traversing a square butt weld joint of the same design configuration used for fusion welding. A plunge load is imparted through a spindle, driven by a FSW machine and reacted against a backside anvil. Frictional heating under the pin tool and around the pin tip generate sufficient heat to locally plasticize the aluminum alloys to be welded. Tool rotation during the FSW process imparts a material flow in three

dimensions to the plasticized weldment, causing complete mixing of the alloys. Consolidation of the weldment occurs via an extruding/forging action under the pin tool shoulder as the pin tool is traversed down the length of the weld. See Figure 1 for a schematic representation of the FSW process.

FSW enjoys a number of advantages over fusion welding processes including the elimination of welding consumables such as gas, filler wire and electrodes. As a joining process based on frictional heating due to mechanical work, FSW has only three primary weld variables to control. These are plunge force, rotation speed and weld travel speed.



**Schematic Of FSW**

**Figure 1. Friction Stir Welding Process**

The 2XXX series aluminum alloys have long been the workhorse of aerospace programs for high strength, lightweight applications. New materials such as Al2195 Aluminum-Lithium alloy provided significant base material improvements over its predecessor Al2219. Improved strength at both room and cryogenic temperatures were significant benefits of the new alloy, however weldability was sometimes a challenge, which prompted efforts to improve the process and ultimately led to the development and implementation of FSW. Al2195 alloy has

proven to be highly receptive to the FSW process, overcoming some of the production difficulties experienced in early development and implementation of Al2195 with conventional fusion weld processes. [2]

### Inspection of Friction Stir Welds

Attendant with the new Friction Stir Weld process, are new inspection requirements for both visual and NDE techniques. FSW enjoys freedom from most fusion weld process defects, however the demands of many aerospace applications require proof testing as well as full NDE of man rated hardware.

Existing processes such as radiographic and penetrant inspections will remain for FSW inspection, however they will be supplemented by new automated NDE. Long term, the automated NDE will replace part of the conventional NDE and ultimately achieve a productivity enhancement for inspection.

Understanding the potential flaws for the FSW process requires an understanding of the metallurgy. Figure 2 provides a cross-section view of a completed FSW allowing one to observe the metallurgical structure associated with a FSW of AL2195.

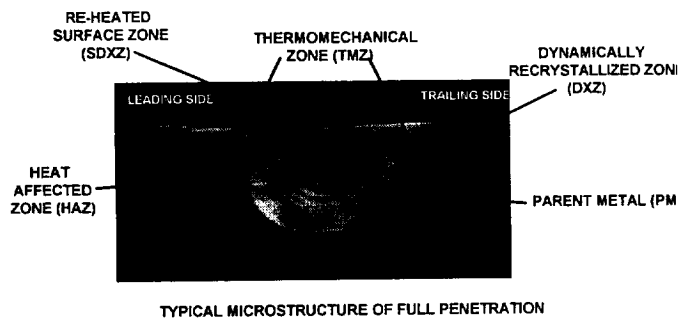


Figure 2. FSW Microstructure

The FSW nugget is formed as frictionally heated metal flows around the pin tool and consolidated under the shoulder. Flaws observed during FSW development present a challenge requiring a blend of several complementary NDE methods to provide adequate inspection. The flaws observed during FSW development range from surface defects such as excess flash, to lack of fill under the FSW tool shoulder, to internal porosity and Lack Of Penetration. (LOP).

In every case the FSW flaw was linked to one or more FSW process conditions or parameters that were related directly as causative factors for the defect.

To assess and select appropriate NDE techniques a logic diagram was generated to integrate candidate NDE techniques, testing and development for NDE, procedures and documentation, process validation and the requirements of fracture control. Factors assessed in evaluating NDE techniques included the Critical Initial Flaw Size (CIFS), potential flaws detected by a given method, the capability of candidate NDE techniques, and their maturity for production use. This assessment has explored a wide variety of NDE methods encompassing visual, several liquid penetrant techniques, ultrasonic inspections of differing types, radiography, and eddy

current. One of the newest NDE technologies assessed was MWM<sup>®</sup> conductivity, a technique that maps surface conductivity in the area of the weldment.

### Visual Inspection

Perhaps the most straight forward and simplest inspection technique, visual inspection is an excellent means of inspecting for surface features including excess flash, galling, shoulder voids, and even weld misalignment. Figure 3 shows an example of a shoulder void.

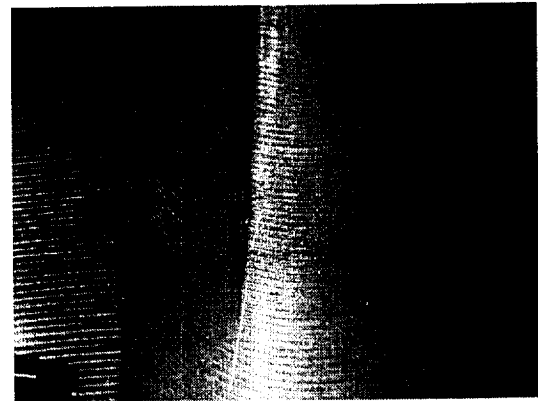
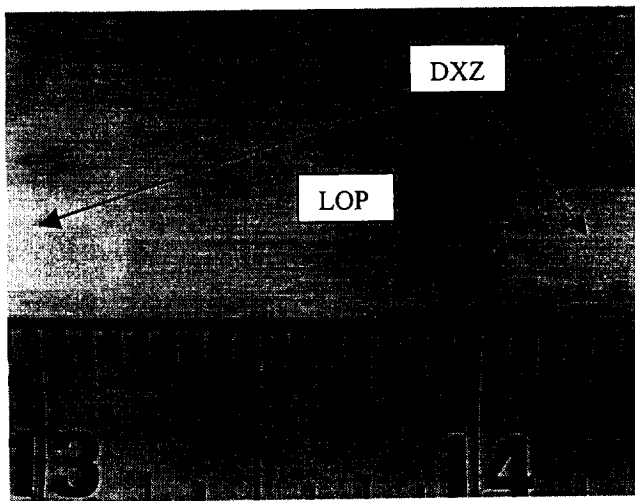


Figure 3. Shoulder Void in FSW.

Workmanship standards were constructed to illustrate acceptable and unacceptable crown and root side surface conditions such as these. These defects are visible to the naked eye, are attributed to out of family welding parameters; such as excessive travel speed (IPM), excessive rotational speed (RPM), inadequate plunge force loads, and improper seam tracking.

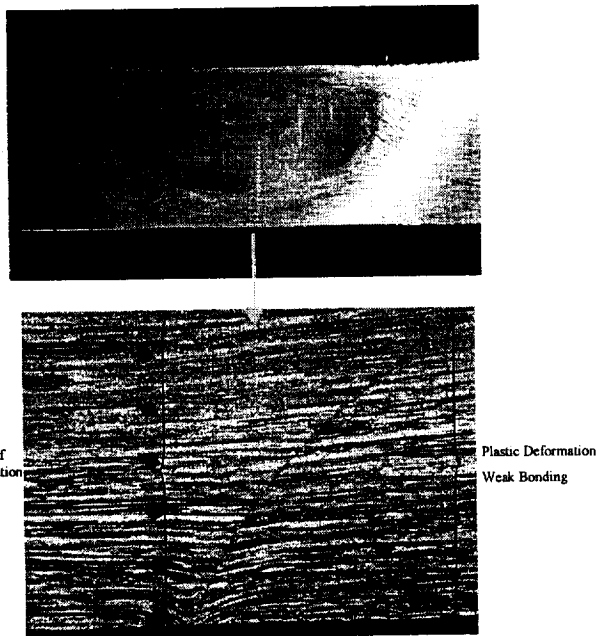
The principle unacceptable root side condition is LOP. Of all of defects, LOP was considered, early on in the friction stir welding program, to be the most critical type of defect. As a result, most NDE testing was conducted with this flaw type.

Visual examination of the root side of the weld demonstrated that LOP flaws were detectable, when inspected in the post etched condition. Etching is a post weld chemical treatment performed most often to prepare mechanically worked surfaces prior to penetrant inspection. In this case, the etching process clearly delineates the weld nugget Dynamically Recrystallized Zone (DXZ), and its surrounding Heat Affected Zone (HAZ) making the lack of FSW nugget a distinct feature visible to the trained eye. The cause for the successful detection rate is due to the fact that it is easy to discern the DXZ from the surrounding parent material and HAZ in the post etch condition. Therefore, visual inspection is a reliable technique to confirm suspected LOP conditions. Figure 4 is a 3X magnification view of an LOP defect on the root side of a FSW panel after etching.



**Figure 4. LOP in FSW after post weld etch.**

The metallurgical characteristics of the LOP flaw are the determining aspects of the flaw and relate directly to the ability of ultrasonics and penetrant inspection techniques to detect LOP. These characteristics are likewise, directly linked to the weld process itself. Primary factors affecting the LOP during welding include heat input or material flow, and most importantly, the depth of the FSW pin tool.



**Figure 5. Metallurgical cross section of LOP flaw.**

Figure 5 illustrates the metallurgical features which include the total depth of LOP, the depth of plastically deformed material and the tight bond at the LOP interface. The most significant of these with regard to NDE, is the degree of "tightness" of the "kissing bond" created at the LOP interface. Conventional NDE techniques rely heavily on a physical separation, void or air gap, as the means to provide a response from such a defect. The less significant this separation, the more problematic is its detection.

## Penetrant Inspection

Penetrant inspection via P135E and P6F4 was performed on FSW test panels in the as welded, single etch, and double etched condition. In addition, penetrant inspections were performed with and without developer, and with varying penetrant dwell times. Penetrant inspection of the FSW test panels in the as welded condition was determined to be an unacceptable method, due to poor detection and the excessive background noise produced by the surface, which interferes with the inspection.

Inspection of FSW in the etched condition via P135E and P6F4 consistently and successfully detected root side LOP flaws. However, because the sensitivity level of detection for each penetrant solution is different, the results were dissimilar. P135E successfully detected LOP flaws that were greater than or equal to 0.064" deep, and P6F4 successfully detected LOP flaws that were greater than or equal to 0.050" deep. Double etching, via caustic etchant solution, prior to the application of penetrant enhanced the detection of LOP in comparison to single etching.

The difference between single etching and double etching is that single etching removed 0.0002" to 0.0004" of metal and double etching removed 0.0004" to 0.0006" of metal. Test results demonstrated that etching to remove a minimum of 0.0004" of metal prior to the application of penetrant improved the detectability of LOP.

Due to the outcome of the test results it was decided that penetrant inspection include the removal of 0.0004" to 0.0006" of metal via caustic etch solution prior to the application of penetrant solution. In addition, extended penetrant dwell times and the use of developer were evaluated and the results yielded no improvement in the detection of LOP flaws.

## Ultrasonic Inspection

AIS (Automated Inspection Systems), RD/Tech, Lockheed Martin, and MSFC NDE engineers and technicians performed ultrasonic inspection on FSW test panels. Conventional UT as well as multi-element probes were evaluated, as were L wave and shear wave techniques and multiple angle transducers. The results initially demonstrated that the technique(s) could detect LOP flaws at 15% to 20% of the material thickness or greater.

However changes in FSW tooling directly affected the LOP flaw metallurgical characteristics, making the flaw more tightly closed and thus more difficult to detect. This affect of improving the weld process without sufficient regard for its effects on other parts of the manufacturing process, including inspection became a recurring theme in pursuing automated NDE. Ultimately, improvements to RD/Tech Phased Array UT inspection technique resulted in detection at 25% to 30% of thickness and greater.

The response for Phased Array provides multiple views of the FSW at one time, allowing position location information, as well as through thickness data to be portrayed for detected flaws. This is accomplished through the use of a 32-element probe, electronically rastering the UT beam across the weld as

the probe is automatically scanned down the length of the weld. The result for an LOP flow is depicted in Figure 6.

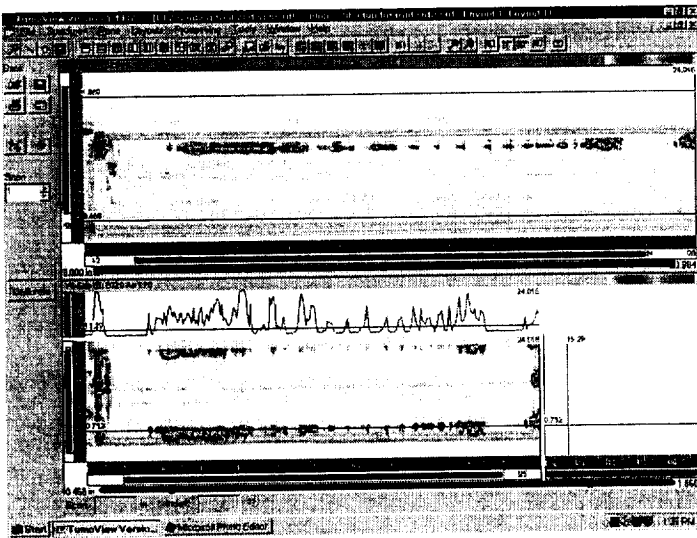


Figure 6. Phased Array scan of LOP flow.

The top portion of Figure 6 provides a C-scan image of the weld with the weld and the flaw running from left to right. The lower portion of the figure is a longitudinal side view showing the material thickness and the location of the flaw at the bottom of the image, which is the root side of the weld. Note detection is discontinuous at some points, which again relates to the metallurgical nature of the LOP flaw.

### Radiographic Inspection

Radiographic inspection was performed via film and digital methods on FSW test panels. Test results demonstrated that we could reliably (90% probability / 95% confidence) detect LOP flaws that are greater than or equal to 30% of the material thickness. However, dissimilar alloy welds posed a challenge in film radiography, in that it is difficult to discern an LOP flaw.

The reason for this is two-fold. First the joining of dissimilar alloys aluminum yields a weldment that is a commingling of the two alloys, which vary in chemical composition by several percentage points of copper and lithium. The difference in copper, greatly affects transmission of the X-ray, requiring an interpreter to "train" his eyes to accurately interpret the film radiograph. Figure 7 provides a view of the metallurgical difference evident in a dissimilar alloy weld of Al2219 to Al2195. The lighter etched portion is Al2219, and the wavy boundary where the two alloys intermix is reflected in radiographs of these welds.

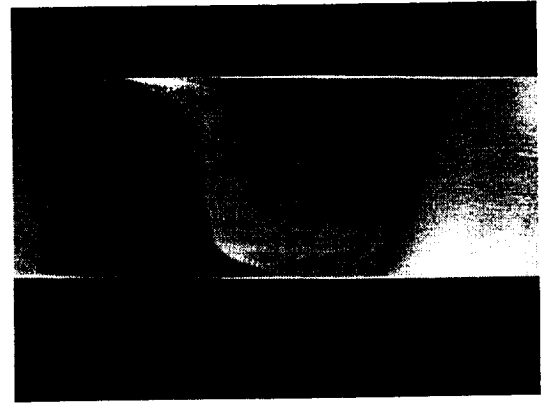


Figure 7. Al2219 to Al2195 Dissimilar Alloy FSW.

The second reason for harder detectability in dissimilar alloys FSW is the tendency for the LOP flaw to be more tightly bonded in this alloy combination (Al 2219 to Al2195). Several in-depth studies of the metallurgy of the FSW has proven the relationship, mentioned earlier with the characteristics of the LOP and its NDE detectability.

### Eddy Current and Conductivity Inspection

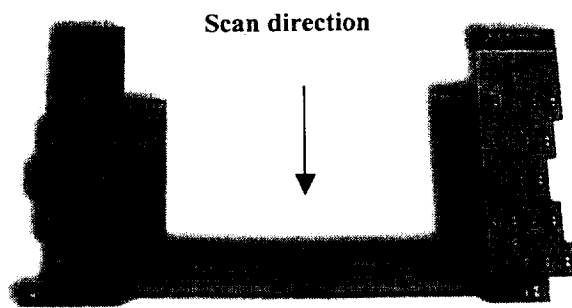
Conventional Eddy Current inspection was performed on FSW test panels by the use of a 1 MHz pencil probe, and a 300 kHz differential rotating probe. Initial Eddy current (EC) results demonstrated reliable detection by both MSFC and Lockheed Martin techniques for Al2195/Al2195 friction stir welds containing at least 0.065" or deeper LOP. The extreme difference in EC across dissimilar alloy welds yielded an EC response from virtually all panels making discrimination of LOP versus No LOP panels unreliable. These promising results changed as changes were made to improve the FSW process by changing the FSW tooling.

Reliable detection during automated NDE is critical to the integrity of aerospace applications. To assess the latest technology other than conventional EC, Lockheed Martin approached Jentek Sensors, Inc. to develop their technology for FSW inspection.

This new approach to EC type inspection is based on conductivity, first explored under LMCO IRAD activity [3]. Jentek Sensors, Inc. was asked to perform various tasks from 1998 through 2001 relative to process monitoring and post weld inspection with their inspection systems.

The promising results of their MWM<sup>®</sup> conductivity methods resulted in a contract to complete technique development and a custom sensor design specific for FSW applications. This work has been completed and provides a risk mitigation complimenting the current plans for radiographic, penetrant and ultrasonic inspection techniques for production NDE of FSW.

The multi-element MWM<sup>®</sup> sensor, Figure 8, has demonstrated detection of 0.050-in. and deeper LOP in Al2195-to-Al2195, as well as in dissimilar alloy Al2219-to-Al2195 FSWs [4].



**Figure 8. Jentek MWM Multi-element Sensor.**

The Jentek MWM<sup>®</sup> system consists of a PC or Laptop computer, Gridstation Software, Instrumentation Module and MWM<sup>®</sup> probe and sensors.

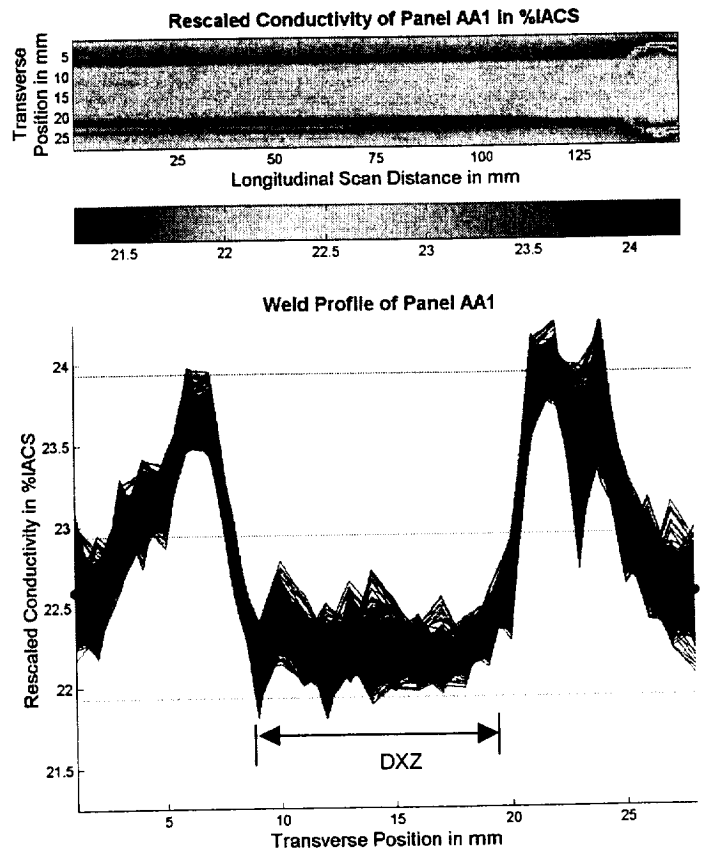
The conductivity probe provides automated scanning, however it is easily used in manual mode as well. Like the multi-element UT probes, the Jentek sensor is comprised of some 37 elements. The MWM-Array employs approximately 30 elements in the primary area of the weldment, with the remaining elements spaced approximately 3 inches apart to track the edges of the weld land. Individual element spacing and arrangement was customized to achieve optimum sensitivity for flaw detection.

Absolute electrical conductivity is a physical property of these aluminum alloys measured by the MWM-Array. Conductivity has long been used to inspect for heat treat condition in aluminum alloy knowing its relationship to changes in alloy composition and metallurgy. Its application for FSW inspection actually maps conductivity on the root side of the weld with a precision more than an order of magnitude better than other conductivity applications. Data is then processed and displayed as a conductivity map at the weld root surface. A C-scan image and profile image for a good weld is shown in Figure 9.

The C-scan view presents the inspection data as a top down view of the Friction Stir Weld. The weld in Figure 9 extends from left to right. The circular region on the right edge of the image is the terminus of the weld, and the yellow region indicates the FSW weld nugget (DXZ) exhibiting full weld penetration through the joint thickness.

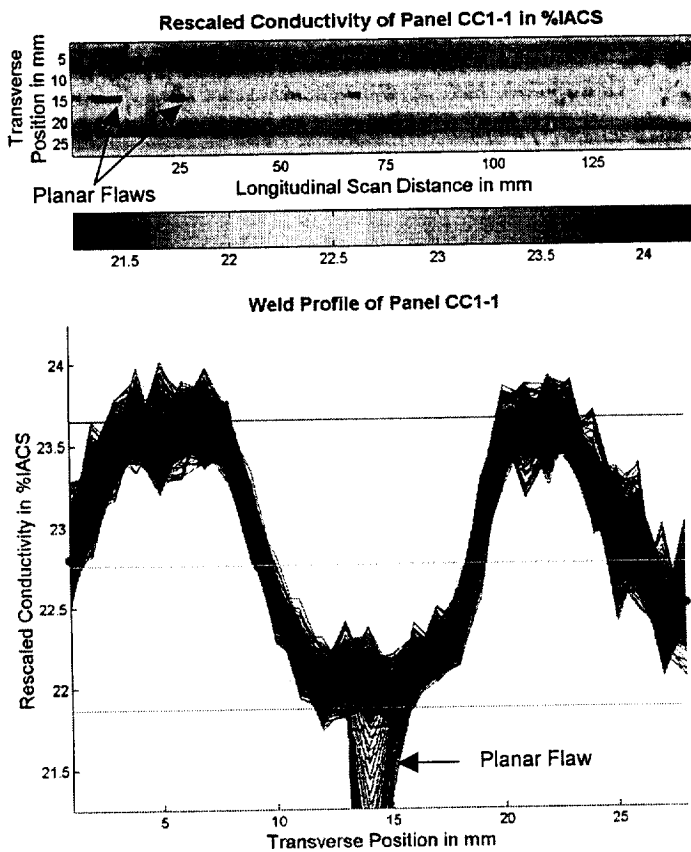
The lower portion of the image in Figure 9 is a cross-section view of the inspection data. FSW DXZ is indicated in the middle of this profile view, while higher conductivity values, on either side of the DXZ, indicate changing conductivity in the Heat Affected Zone (HAZ). Blue to aqua colored zones map the HAZ on either side of the DXZ.

**Figure 9. Full Penetration FSW Conductivity Map.**



LOP, the failure of the FSW to fully penetrate the joint thickness, presents itself as significantly different conductivity patterns as illustrated in Figure 10. This FSW specimen contained 0.045" deep LOP and exhibits minimal DXZ, as well as several planar flaw indications.

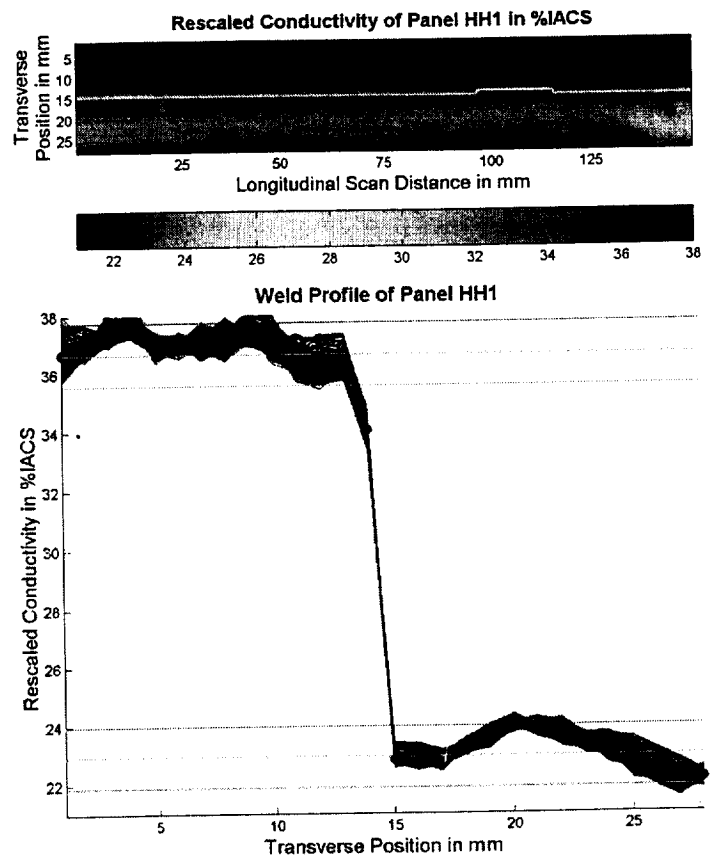
Comparison of the profile in Figure 9 to that of Figure 10 reveals differences in conductivity values and their position are observed as changes to the shape of the profile. The presence of planar flaws is also noted as severe reductions (drop out) in the conductivity profile noted in Figure 10.



**Figure 10. FSW with LOP Conductivity map.**

Dissimilar alloy FSW yield quite different patterns of conductivity via the Jentek MWM-Array technique due to the large differences in parent material conductivity. Al2219-T8 exhibits a typical conductivity of 34% IACS, while Al2195-T8 is 20. The profile in Figure 11 shows the high conductivity Al2219, to the left of the profile, decreasing rapidly as the conductivity drops into the DXZ area. The DXZ is bounded on either side by slight peaks in conductivity indicating the HAZ.

The specimen for this example contained LOP 0.057" deep. The key to developing criteria for detection of LOP via this technique lies in differences affecting the shape of the conductivity map include a sharp changes in the slope (rate of decrease) in conductivity from the Al2219 side of the FSW and a reduction to the extent of the weld DXZ.



**Figure 11. FSW LOP Conductivity map dissimilar alloy.**

## Summary

NASA and Lockheed Martin are pursuing implementation of Friction Stir Welding (FSW) and automated NDE as part of a larger program to improve performance, safety and producibility for welded aerospace hardware. FSW is being implemented to take advantage of its high strengths and toughness, and its near defect-free welds in 2XXX aluminum and aluminum lithium alloys used for numerous aerospace applications.

Significant productivity gains are anticipated due to transitioning from conventional manual NDE inspection techniques to automated production NDE. Existing NDE methods including liquid penetrant and radiography will continue as automated Phased Array ultrasonics is implemented, and subsequently used to replace manual NDE.

To assure risk mitigation for conventional NDE inspection techniques a new technology utilizing MWM® conductivity mapping technique with a custom 37-element array sensor specific has been accomplished.

## Acknowledgments

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## References

1. W.M. Thomas, et al.: "Friction Stir Butt Welding", International Patent Appl. No. PCT/GB92/02203 and GB Patent Appl. No. 9125978.8, Dec. 1991, U.S. Patent No. 5,460,317
2. William Arbogast, Paula Hartley: "Friction Stir Weld Technology Development at Lockheed Martin Michoud Space Systems – An Overview", June 1998, AEROMAT.
3. Neil Goldfine, William Arbogast, et al.: "Friction Stir Weld LOP Defect Detection Using New High Resolution MWM-Array and Eddy-Current Sensors", June 2001, AEROMAT.
4. David G. Kinchen, Neil Goldfine, et al.: "Friction Stir Weld Inspection Through Conductivity Imaging using Shaped Field MWM® Arrays", April 2002, Trends In Welding Research.